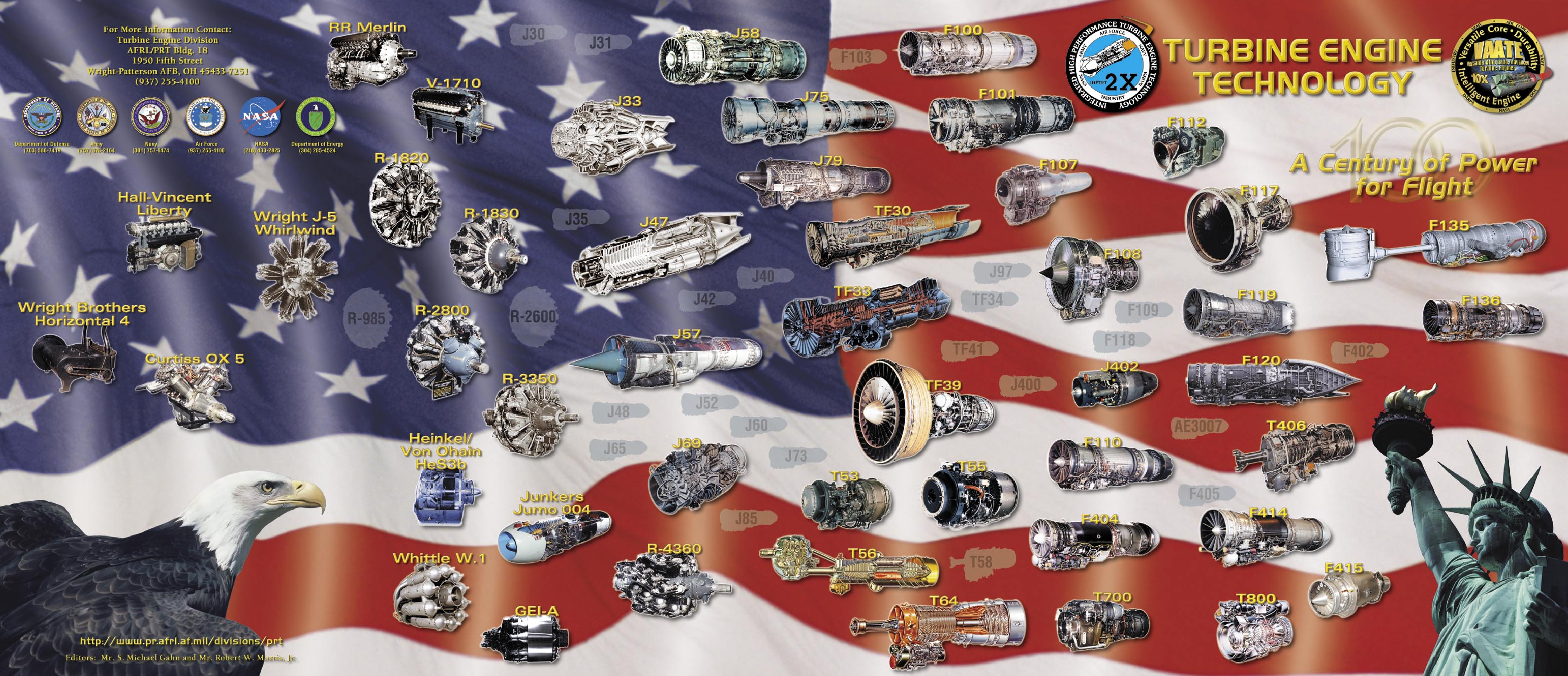

TURBINE ENGINE TECHNOLOGY
A Century of Power for Flight
100
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A CENTURY OF POWER FOR FLIGHT...

The Wright Brothers, Wilbur and Orville, were bicycle makers from Dayton, Ohio who achieved the first controlled, manned, powered flight on December 17, 1903, in an airplane which they designed, built, and took turns piloting. Prior to their success, they mastered an understanding of the aerodynamics of lift and drag, lightweight structures, stability and control, and of course, propulsion. They studied the work of others, verified and extended it, kept their own counsel when their experiences ran counter to the experts, invented, adapted, and perfected their work at every turn. Since they could find no suitable engine for their airplane, Orville designed one based on the simple unit they had constructed to power the machine tools in their cycle shop. Their mechanic, Charlie Taylor, built it using aluminum, a new lightweight material, for the block. Their engine produced 12 horsepower and weighed about 200 pounds. Finding little useful information on the theory of propellers, they conducted their own experiments and built a successful propeller which, when combined with their revolutionary engine, was enough to change the world.

In the ensuing decades, airplane piston engines were built in numerous sizes, shapes, and designs: air cooled and liquid cooled, radial, Vee, and in-line cylinder configurations, with fuel injection or carburetion, poppet valves and sleeve valves, normally aspirated and supercharged. Even within each of these designs, there were many different approaches.

Supercharging is a good example. Early on, it was realized that the limiting factor to achieving high altitude flight was the loss of power that a normally aspirated engine experiences as it ascends to thinner air. To concentrate more air into the combustion chamber, superchargers were introduced and configured with the compressor directly driven from the crankshaft, driven by exhaust gas, or combinations of the two. Intercoolers were sometimes included to cool the supercharged air, producing more power and decreasing engine knock. By the mid-1920s, variable pitch propellers were invented to optimize prop pitch with flight speed.

In WWII, American industry built hundreds of thousands of aircraft engines that delivered victory into the hands of the Allies. Some of the more notable engines include the Wright R-1820 (B-17), Pratt & Whitney R-1830 (B-24 and C-47), Allison V-1710 (P-38), Pratt & Whitney R-2800 (P-47, F-8U and C-46), and the Rolls-Royce developed, Packard built Merlin (P-51). The V-1710 powered America's two top aces of the war, Major Richard Bong and Major Thomas McGuire, to a total of 78 victories. While development of the piston engine was curtailed dramatically with the advent of the jet engine, many types of piston engines powered America's aircraft through the Korean and Vietnam Wars.

Progress in piston powered aircraft can be appreciated by considering that the propulsion system of the Wright Brothers' 1903 airplane had a power-to-weight ratio of 0.04 Hp/lb and an overall efficiency (the product of thermal and propulsive efficiencies) of about 5%. By the end of WWII, the power-to-weight ratio of piston powered aircraft had improved by more than an order of magnitude and the overall efficiency by a factor of five.

The jet engine was concurrently and independently invented and developed by both Frank Whittle in Great Britain and Hans von Ohain in Germany prior to WWII. While the Whittle and von Ohain engines both ran in 1937, the Germans were first to fly a jet airplane and build a jet fighter, the twin engined Me 262, which saw action in the last months of the war. To power it, they built thousands of Junkers Jumo 004 jet engines. The Me 262 was 100 knots faster than the Merlin powered P-51, the fastest fighter America had in the skies. While the Me 262 was too little too late for the Germans, it clearly showed the superiority of jets.

In Britain, jet engine development also progressed rapidly and soon attracted the attention of USAAF General "Hap" Arnold. In 1941, after witnessing a flight of the Whittle-powered Gloster E28/39 jet prototype, he negotiated with the Air Ministry to produce the Whittle/GEI-A in the United States. From this British "seed" engine, much of the US jet aircraft engine industry took root.

Jet engines were a paradigm shift in technology and immediately new US aircraft developments were based on them. Jet engines powered all new US fighters beginning with the P-80, and all bombers beginning with the B-47.

While jets offered terrific speed, they were notoriously fuel hungry and short lived. Through cycle analysis, it was known that higher thermal efficiency required a higher cycle pressure ratio, and a corresponding increase in turbine inlet temperature. In the late forties, the generally acknowledged pressure ratio limit for a multistage axial flow compressor with fixed stators was about 6:1. Above that value, the compressor simply was not operable; it could not be started at low rpm nor accelerated to high rpm without stalling. Since the rotor and stator angles were set to produce high pressure ratio at high rpm, the angles were far from optimum at low rpm.

In the US, Pratt & Whitney led the way with a successful high pressure ratio (12:1) design consisting of two separate compressors in series (one with nine stages and one with seven stages). The two compressors ran at different rotational speeds and were only aerodynamically coupled. Pratt & Whitney's two spool compressor development was the foundation of the J52, J57, and J75 series of military engines and the JT3 and JT4 series of commercial engines.

General Electric's approach was to design a single spool 17 stage axial flow compressor with variable stators to prevent rotor blades from stalling. These controllable stators, or the variable geometry compressor as it came to be known, were the foundation for the J79 series of military engines and the CJ805 series of commercial engines.

Both the dual (and even triple) spool and variable stator configuration compressors would come together a decade later in the high bypass turbofan engines powering wide body aircraft.

Because of its high power-to-weight ratio, the jet engine in the form of a turboshaft also became the engine of choice for low subsonic speed, fixed-wing aircraft and helicopters. Engines such as the Lycoming (now Honeywell) T53 and T55, the Allison T56, and the General Electric T64 have been in production and operational use for nearly 50 years.

Turbofan engines supplanted the pure jet in both military and commercial applications beginning in the early 1960s. While the earlier doubling of the compressor pressure ratio had improved the thermal efficiency of the jet engine, the propulsive efficiency was improved with the turbofan cycle. The Pratt & Whitney JT3D/TF33 family of turbofans dominated early US commercial (Boeing 707 and Douglas DC-8) and military (C-135, B-52H, and C-141) applications for turbofan engines.

THE IHPTET TEAM...

In December of 1902, Charlie Taylor began construction of the engine that would, one year later, take man aloft in powered flight for the first time. Over the next century, spectacular gains in aircraft propulsion would contribute heavily to America's freedom and standard of living. Advances in aircraft propulsion are continuing through the Integrated High Performance Turbine Engine Technology (IHPTET) program, whose goal is to double propulsion capability by 2005.

The first afterburning turbofan, the TF30, powered the F-111 multirole fighter. Afterburning turbofans, with bypass ratios of one or less, provide both good subsonic cruise fuel efficiency and high augmented thrust for supersonic flight. Even today, the afterburning turbofan remains the dominant cycle for all fighters.

High bypass turbofans, meaning bypass ratios in the range of 5 to 9, power virtually all transports designed to cruise at high subsonic speeds. High bypass ratio engines provide increased takeoff thrust, low environmental noise, and low specific fuel consumption. The development of the first high bypass ratio turbofans, the TF39 for the C-5A and the JT9D for the Boeing 747, required nearly doubling the cycle pressure ratio from the 12:1 of the JT3/J79 series of jets, and increasing the turbine inlet temperature. The newest high bypass turbofans have cycle pressure ratios greater than 40:1 and have been made possible by advancements in high temperature materials and cooling technology. In a general sense, increases in hot section materials capability and turbine cooling techniques have paced the development of high pressure ratio engines. Today, turbofans range in size from small missile engines by Teledyne and Williams International, to behemoths in the 100,000 pound thrust class for large transports.

In 1987, the Integrated High Performance Turbine Engine Technology (IHPTET) program was established to double aircraft propulsion capability. Supercruise (supersonic flight without afterburner) and advanced STOVL (Short Takeoff Vertical Landing) are made possible by investments in IHPTET technologies that are transitioning today to the F-22 and F-35.

For the future, the DoD, DOE, NASA, and industry program known as Versatile, Affordable, Advanced Turbine Engines (VAATE) will assure further dramatic improvements in turbine engine affordability, not only for military applications such as aircraft, rotorcraft, missiles, and Unmanned Air Vehicles (UAVs), but also for America's domestic applications. VAATE will develop technologies that enable affordable growth to legacy systems and provide propulsion and power for future air, land, and sea applications.

IHPTET GOALS ARE BEING DEMONSTRATED...

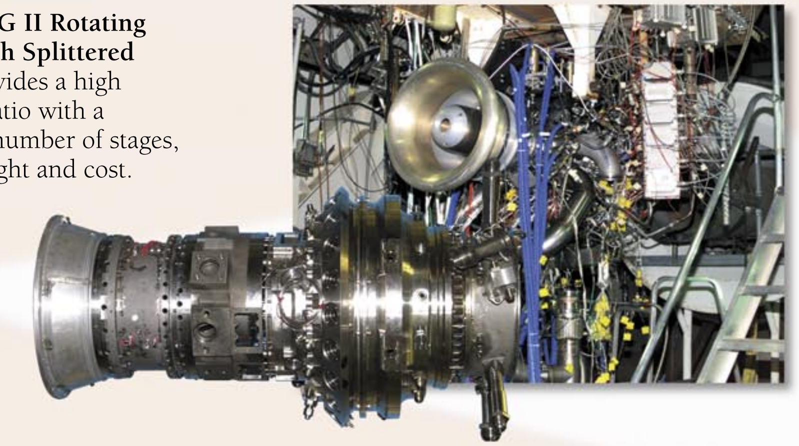
The IHPTET program is a national collaborative effort among the Air Force, Navy, Army, NASA, DARPA, and industry to double aircraft propulsion capability by 2005. IHPTET Phase I is complete, Phase II demonstrators are on test, and development of Phase III performance and structural demonstrator engines are underway. Joint service technology demonstrator cores and engines running with IHPTET developed components have validated improvements in advanced design, rules and tools, performance, life, and cost. The Advanced Turbine Engine Gas Generator (ATEGG) and the Joint Technology Demonstrator Engine (JTDE) validate the large turbofan/jet class of engine technologies. The Joint Turbine Advanced Gas Generator (JTAGG) demonstrator represents the small-to-medium size turboshaft/prop/fan class. The Joint Expendable Turbine Engine Concept (JETEC) demonstrates expendable and limited life engine technologies. These demonstrators provide low risk technology transition, resulting in high readiness and increased safety and performance for the warfighter.

IHPTET ACHIEVEMENTS...

PHASE II JTAGG

This JTAGG II Rotating Group with Splittered Rotor provides a high pressure ratio with a minimum number of stages, reducing weight and cost.

High Effectiveness Advanced Turbine (HEAT™) Blades operate at high temperatures with a minimum expenditure of cooling air to reduce fuel consumption.



The Honeywell XTC56/2 Phase II JTAGG will demonstrate an 89% increase in Horsepower-to-Weight (Hp/Wt) and a 29% reduction in Specific Fuel Consumption (SFC), resulting in a simultaneous 60% range and 10% payload increase for attack missions with a 20% reduction in Operation and Support (O&S) costs.

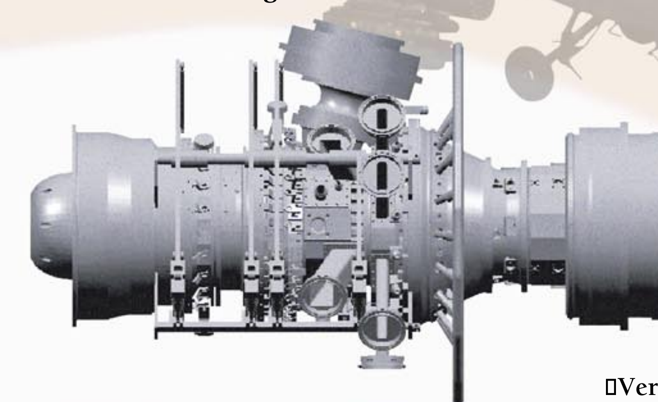
PHASE III JTAGG

This Splittered Rotor with Improved Aerodynamics produces a high pressure ratio in a single stage.

The Forward Swept HPC was successfully validated in rig testing. It offers high efficiency, high pressure ratio, and increased operability in a compact stage.

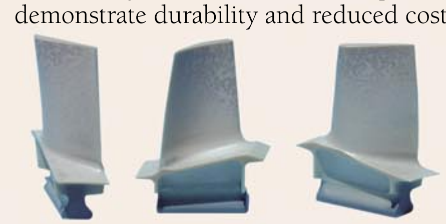
The High Temperature Rise Combustor features a Ceramic Matrix Composite (CMC) liner with an advanced dome. The combustor demonstrated a low pattern factor at the goal fuel-to-air ratio resulting in higher performance.

The Honeywell/General Electric XTC97 Phase III JTAGG will demonstrate the goals for Hp/Wt and reduced SFC, resulting in a 100% range increase or 30% payload increase, with 50% less fuel burn for a cargo mission and 35% reduction in O&S costs.



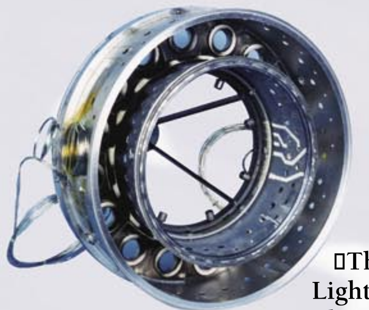
This High Pressure Compressor (HPC) Impeller with a Split Inducer/Exducer incorporates forward sweep for high efficiency. Rig testing of this design has demonstrated suitability for use in JTAGG III.

Monolithic Ceramic Low Pressure Turbine (LPT) Blades have been successfully tested for burst and tip rub to demonstrate durability and reduced cost.



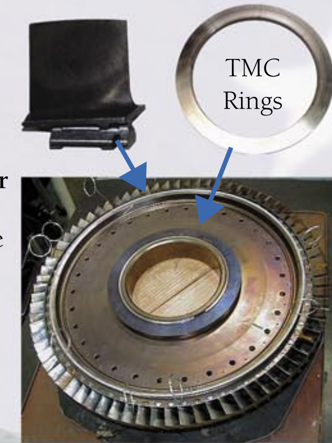
Very Small High Pressure Turbine Blades, made from advanced MX4 materials, have been water flow tested to verify cooling flow and represent the latest 3-D shape for high efficiency.

PHASE II ATEGG



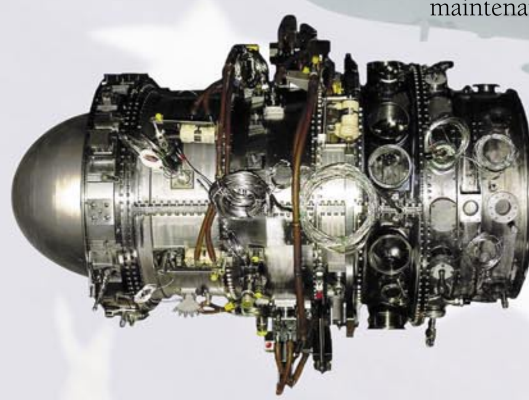
This Lightweight, High-Temperature-Capable, Flex Liner Design delivers full life durability and reduced life cycle cost.

Silicon-Carbide (SiC) Fiber Reinforced SiC Matrix Composite Liner Technology will allow for a combustor wall capable of 2400°F to meet performance objectives.



This Advanced Compressor Rotor combines gamma titanium aluminide blades with a high temperature Titanium Matrix Composite (TMC) ring construction, resulting in cost effective weight reduction and improved maintenance features.

The MA754 Material in this Combustor Liner provides a 200°F increase in metal temperature capability.

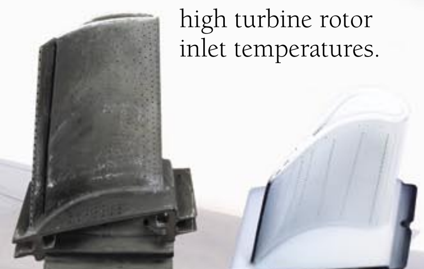


The General Electric/Allison Advanced Development Company XTC76/3 Phase II ATEGG contains core technologies which contribute to a 48% improvement in engine Thrust-to-Weight (Fn/Wt) and a 30% reduction in SFC.

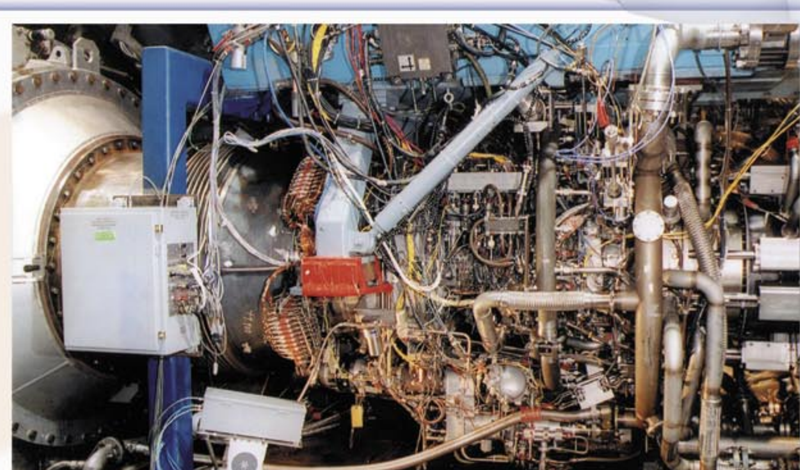
This Variable Area Turbine makes improved SFC possible throughout the flight envelope.

A Core Drive Fan Stage for Variable Cycle Engines dramatically improves performance for multiple design point aircraft.

Hybrid Bearings with Silicon Nitride Rolling Elements provide high load and high rotor speed capability, enabling increased pressure ratio.

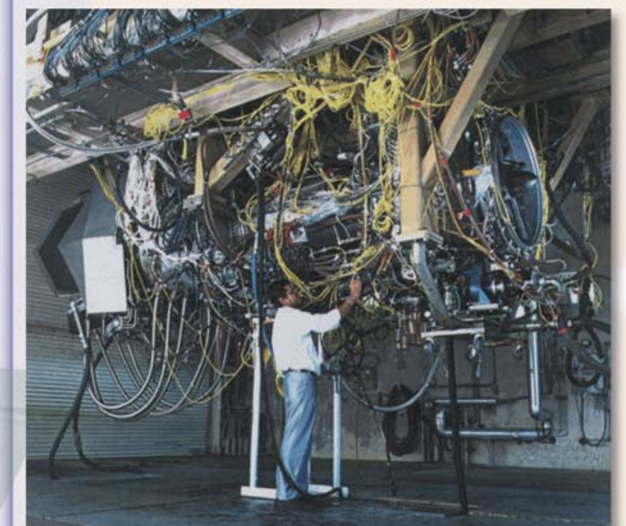


Advanced Cooling Technologies ensure high pressure turbine durability and reduced maintenance costs at high turbine rotor inlet temperatures.



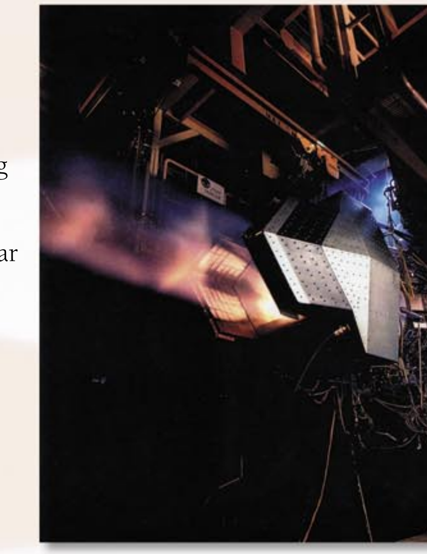
The Pratt & Whitney XTC66/1B Phase II ATEGG successfully demonstrated a high pressure ratio per stage HPC, a high efficiency High Pressure Turbine (HPT) with Superblades and vanes, brush seals, and hybrid ceramic bearings in a core that contributed to a 37% Fn/Wt improvement.

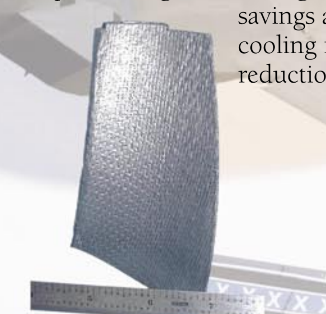
PHASE II JTDE



The Pratt & Whitney XTE66/1 Phase II JTDE demonstrated a 39% improvement in Fn/Wt. It provided an initial assessment of many technologies for the F135 engine that powers the F-35 Joint Strike Fighter (JSF).

This Spherical Convergent Flap Nozzle demonstrated pitch and yaw thrust vectoring and reversing with a 20% weight savings over current 2-D nozzles with similar functions.





This CMC Low Pressure Turbine Vane uses 3-D fiber architecture to increase strength and durability. Its low density and high temperature capability provide significant weight savings and cooling flow reductions.

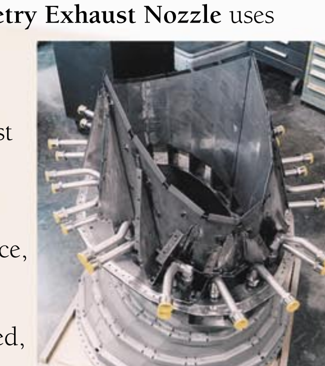
This Turbine Rear Frame provides a path for structural loads, allowing the flowpath components to be made of lightweight, high temperature materials.

The First Stage Fan features forward swept airfoils, high stage loading, low aspect ratio, and increased stall margin.

The General Electric/Allison Advanced Development Company XTE76/1 Phase II JTDE exploits forward swept fan technology; a vaneless counterrotating low pressure turbine; and variable cycle, fixed exhaust nozzle engine architecture to meet the Phase II 60% Fn/Wt goal, providing an initial assessment of many F136 engine technologies for the F-35 JSF.

This Multiproperty Rotor combines the durability properties of a fine-grained, powder metal hub, with the temperature capability of a single crystal rim. It has a 300°F improvement in creep and fatigue capability over current materials, allowing a 1500°F rim temperature.

This Second Stage LPT incorporates 3-D aerodynamics and high cooling effectiveness for improved engine performance.



This Fixed Geometry Exhaust Nozzle uses engine bleed flow to fluidically control the effective throat area to provide thrust vectoring. This significantly reduces weight, complexity, cost, and maintenance, in comparison to a conventional, mechanically actuated, variable nozzle.

PHASE III ATEGG

This IHPTET Government and Industry Test Team successfully demonstrated the Pratt & Whitney XTC67/1 Phase III ATEGG. It contains technologies which contribute to the Phase III goals by validating a 53% improvement in Fn/Wt, a 23% reduction in production costs, and a 19% reduction in maintenance costs.

- **The Impingement Film Floatwall Combustor** demonstrated a low pattern factor with an excellent temperature profile necessary for HPT durability and reduced maintenance costs at high fuel-to-air ratios and increased temperatures.

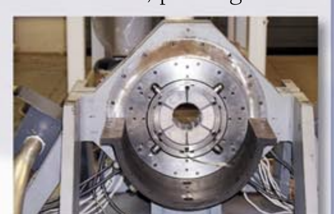
- **This Highly Loaded, Four Stage Compressor** replaces a conventional six stage compressor, providing equivalent performance at reduced weight and cost.

- **This Bonded Dual-Web Turbine Disk** demonstrated a 17% lighter weight disk while increasing rotor speed by 9%.

- **Supercooling and Manufacturing Technologies Incorporated into these Turbine Airfoils** allow high performance, reduced cost, and durable operation at turbine temperatures in excess of Phase II conditions.

- **This Hollow CMC High Pressure Turbine Vane** is 50% lighter and requires 20% less cooling flow than a typical nickel-based superalloy vane.

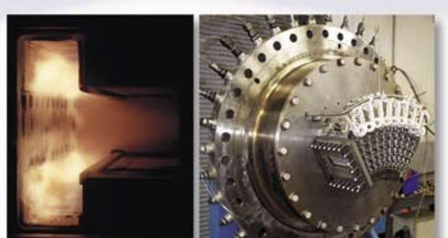
- **This High Pressure Compressor** met performance requirements and no aeromechanical issues were identified during rig testing.



- **This Radial Magnetic Bearing** ran at 1000°F, proving the capability of electromagnetic technology. The technology provides nearly frictionless rotor support in environments up to 600°F higher than conventional liquid lubrication.

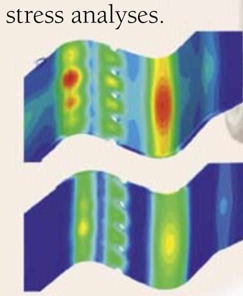
The General Electric/Allison Advanced Development Company XTC77/1 Phase III ATEGG program will develop and demonstrate core technologies that contribute to an 85% improvement in Fn/Wt.

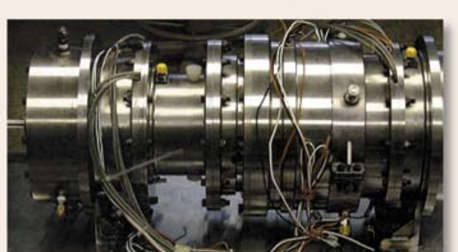
- **This Mist Lubricated, Continually Rotating Auxiliary Bearing** uses a carbon-carbon cage and silicon nitride balls to provide load sharing with a magnetic bearing.



- **The Trapped Vortex Combustor Sector Rig Test** has demonstrated improved flame stabilization, re-light capability, and low fuel-to-air ratio blow out levels.

- **Three-Dimensional Models of the CMC Combustor Liner,** using orthotropic material properties, resulted in improved thermal and stress analyses.



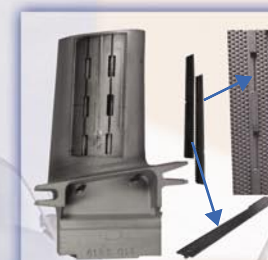


- **Rig Testing to 17,000 RPM** has demonstrated the successful integration of this Magnetic Bearing/Integral Starter/Generator System.

- **A Vortex Controlled Diffuser** reduces engine length, weight, and cost. Stereo lithography models of the diffuser will be rig tested to validate aerodynamic design rules and tools.

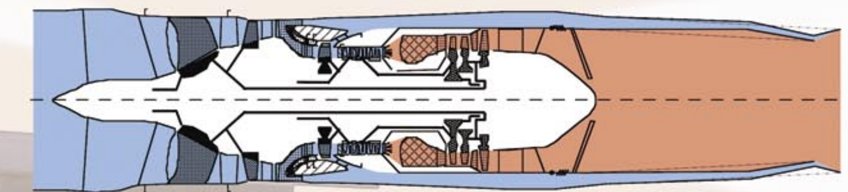
IHPTET ACHIEVEMENTS...

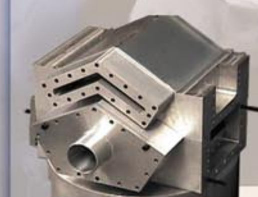
PHASE III JTDE



- **This Tiled Turbine Airfoil Design** enables low cost implementation of advanced materials and cooling concepts.

- **The Flexible FADEC** utilizes a modular design that will allow development costs of the unit to be spread over multiple engine models. It features advanced processors and smaller rectangular connectors which reduce the overall size and lower production and maintenance costs.

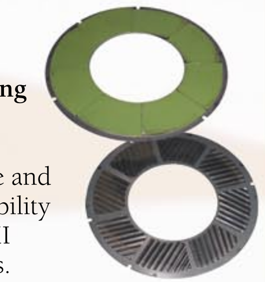




- **Fixed Area Fluidic Vectoring Nozzle Technology,** as shown in this subscale hardware, allows reduced weight, lower cost, and improved vehicle integration.

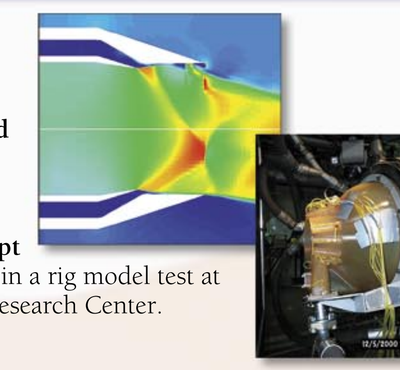
The General Electric/Allison Advanced Development Company XTE77 Phase III JTDE will demonstrate advanced fan, low pressure turbine, and augmentor technologies, offering greater operating margins, enhanced safety, and future growth capabilities for the F136 engine for use in the F-35 JSF.

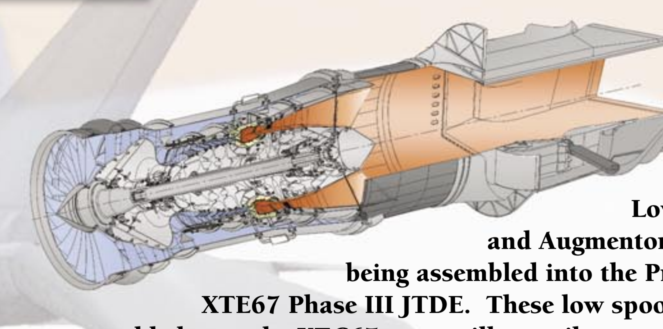
- **This Film Riding Face Seal** offers low air leakage and high durability at Phase III conditions.



- **This Moderate Aspect Ratio Fan** features a linear friction welded, forward swept, low cost, integrally bladed rotor and fixed inlet guide vanes, capitalizing on mistuning technologies for high cycle fatigue mitigation and low cost and weight.

- **Modeling and Simulations of this Fluidic Vectoring Nozzle Concept** were validated in a rig model test at NASA Glenn Research Center.





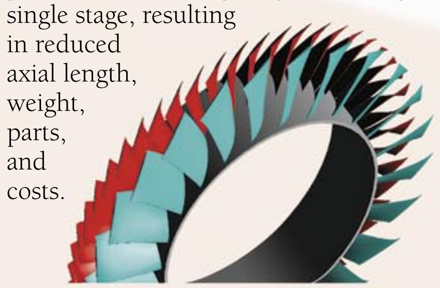
Advanced Fan, Low Pressure Turbine, and Augmentor Technologies are being assembled into the Pratt & Whitney XTE67 Phase III JTDE. These low spool technologies, assembled onto the XTC67 core, will contribute to the demonstration of the Phase III goals, offering greater operating margins, enhanced safety, and future growth capabilities for the F135 engine.

- **This Second Stage LPT Blade** combines advanced low conductivity thermal barrier coatings and ceramic abradable seal coatings to improve durability and performance.

- **The Second Stage LPT Disk** uses lightweight blade attachments which reduce weight by 13.4 pounds, allowing an 11% increase in rotor speed while meeting full life requirements.

- **High Performance Hybrid Bearings, Using Ceramic Elements,** are being developed to enable higher operating speeds, improved surface durability, and extended bearing life.

- **Tandem Fan Rotor Technology** boosts pressure ratio through higher turning in a single stage, resulting in reduced axial length, weight, parts, and costs.



...IHPTET ACHIEVEMENTS

PHASE II JETEC

This Carbon-SiC Composite Turbine Nozzle and Rotor, and Carbon-Carbon Exhaust Nozzle comprise the all-composite, uncooled hot section for increased temperature capability and weight reduction.

The Williams International XTL86 Phase II JETEC ran at Mach 0.8 in an altitude test at Arnold Engineering Development Center. During further testing, the engine exceeded the temperature objective and met the specific thrust and cost reduction goals.

Cageless Fuel Lubed Thrust Bearings enable lighter, lower cost engines due to the elimination of traditional oil-wetted lubrication systems and are transitioning to cruise missile applications.

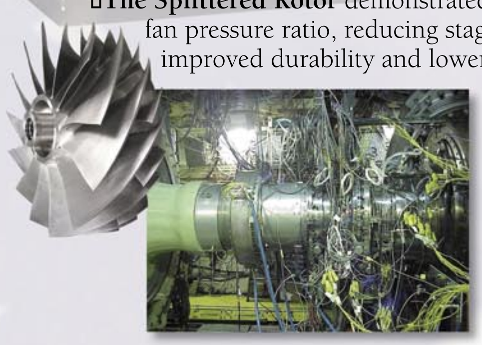
This High Through-Flow, High Velocity Burner demonstrated a 900°F increase in temperature rise over previous builds, increasing specific thrust.

The Oil Vapor-Phase Lubrication System eliminates the need for conventional lubrication, thereby reducing costs.

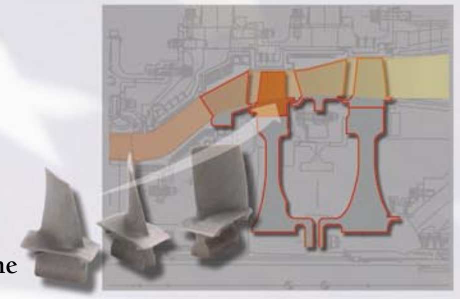
The Allison Advanced Development Company XTL16 Phase II JETEC was designed to reach 76% improvement in specific thrust and 47% reduction in cost.

PHASE III JETEC

The Honeywell XTL57/1 Phase III JETEC, designed for a limited life UAV application, incorporates technologies which enable reduced fuel consumption and cost.



The Splittered Rotor demonstrated high single stage fan pressure ratio, reducing stage count with improved durability and lower cost.



The Low Pressure Turbine is designed with all-ceramic airfoils and a high slope ceramic transition duct for reduced weight and cost, increased performance, and improved fuel consumption.

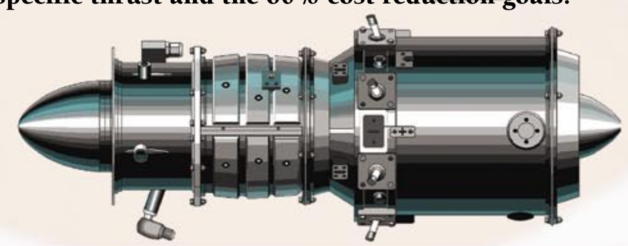
These Molded Fan Blades are part of the composite, forward swept, shrouded fan. The NASA CFD code APNASA is utilized to optimize fan performance.

The Williams International XTL87 Phase III JETEC will have a forward swept, shrouded fan and an uncooled ceramic HPT. It is designed to meet the 40% SFC reduction goal and will exceed the 60% cost reduction goal for limited life engines.

These Silicon Nitride Ceramic Uncooled HPT Blades provide high temperature capability at low cost.

This Carbon-SiC Exhaust Nozzle eliminates the need for exhaust system cooling, which will increase performance and reduce cost.

The Allison Advanced Development Company XTL17 Phase III JETEC is being designed to meet the 100% specific thrust and the 60% cost reduction goals.



This Combustor Liner will use advanced coatings, materials, and cooling concepts to allow operation at near-stoichiometric fuel-to-air ratios.

GOVERNMENT IN-HOUSE R&D CAPABILITIES...

HIGH IMPACT TECHNOLOGIES

Research and Development of IHPTET and future VAATE components are underway in government and industry laboratories and facilities across the nation. Work is ongoing for fans and compressors, combustors, turbines, exhaust systems, mechanical systems, and controls. Pervasive technologies in the areas of materials, computational fluid dynamics, structures, cost reduction, combustion sciences, and fuels are being developed to support the components. State-of-the-art facilities, high fidelity modeling and simulations, and world class scientists are the cornerstone of government in-house R&D.

The Combustor Research Complex develops and evaluates advanced combustor concepts at realistic operating conditions.

The Real Time Virtual Simulator allows simulation of advanced and legacy engines for control system and Engine Health Management (EHM) research.

The Turbine Research Facility (TRF) conducts basic and applied research on modern, full scale, high pressure turbines.

The National Aerospace Fuels Research Complex relies on simulations of aircraft fuel system environments to improve both thermal stability and low temperature operability, and to reduce emissions.

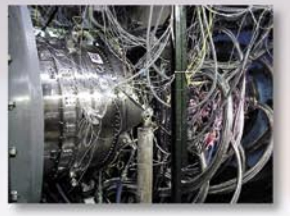
The Combustion & Laser Diagnostics Research Complex (CLDRC) develops methods and collects fundamental combustion data to validate computational design models.

The Mechanical Systems Research Facilities develop advanced bearing and lubrication technology through analysis, modeling, and rig testing of novel materials and lubricants.

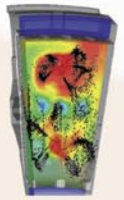
The Pulsed Detonation Research Facility (PDRF) is demonstrating the low cost, high performance characteristics of pulsed detonation engines as propulsion systems for military air vehicles.

The Navy Spin Pit Facility can simultaneously impart both centrifugal and vibratory loads, by means of oil jet or eddy current excitation, to verify structural integrity under more realistic conditions.

The Compressor Aero Research Lab (CARL) conducts fundamental research in compressor aerothermodynamics and develops innovative concepts for future applications.

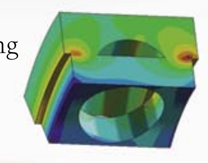


The Compressor Research Facility (CRF) performs full scale fan and compressor component verification testing for demonstrators and fielded systems.

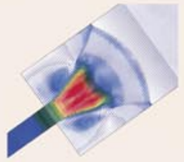


The NASA 3-D Combustor Simulation Code models liquid spray droplet fuel injection for improved combustor designs.

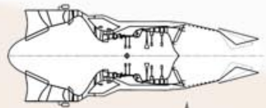
The Bearing System Thermal Management Model optimizes bearing designs which use ester lubricants to meet the challenge of higher performance VAATE engines.

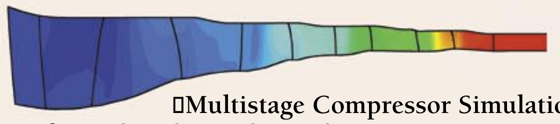


Conceptual Engine Design and System Level Payoff Studies are an integral part of overall modeling, simulation, and analysis capability.

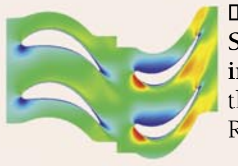


Computational Analysis is used to analyze pulsed detonation combustion.





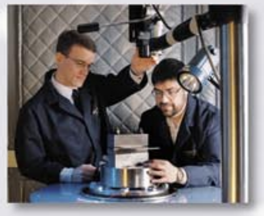
Multistage Compressor Simulations Performed in the Turbomachinery Computational Analysis Facility (TurboCAF) improve the understanding of multistage interactions in compression systems.



Low Spool Turbine Simulations Performed in the TurboCAF improve the understanding of low Reynolds number effects.

The IHPTET and National High Cycle Fatigue (HCF) programs respond to the needs of Army, Navy, and Air Force engines in development and in the field. IHPTET and HCF technologies improve performance and durability, while reducing the cost of operating and maintaining turbine engines in service around the world. Technologies transitioning from these programs specifically address issues such as increased component life, reduced fuel consumption, and increased safety. Nearly all the technologies developed in the IHPTET and HCF programs are also directly applicable to the development of advanced US commercial engines.

HCF



The Turbine Engine Fatigue Facility (TEFF) is responsible for conducting research on the impact of vibration and fatigue on turbine engine components to increase safety and life.

Rotor Mistuning is simulated to obtain a fundamental understanding of blisk response and dynamic motion.

The High Cycle Fatigue Test Protocol has been demonstrated on the XTC67/1. This protocol enables a substantial increase in understanding the design and test parameters that must be undertaken to identify and resolve HCF issues within gas turbine engines. Other demonstrations are planned for the XTC76/3, XTE67/1, and XTE67/SE1.

Laser Shock Peening (LSP) is an innovative process that vastly improves the durability of metallic fan blades, thereby reducing maintenance and repair costs. LSP has been transitioned to the F110 and F101, and is being qualified for the F119, F135, and F136 engines.

SDE

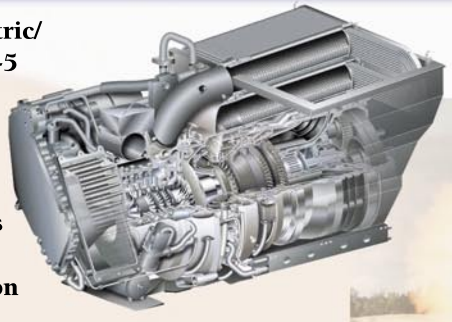
The Allison Advanced Development Company XTL17/SE1 will be used to jointly validate US and UK HCF design tools and passive damping technology. Testing will also demonstrate dimpled turbine blade technology for high altitude performance improvements.

The General Electric XTE77/SE1 durability demonstrator is based on GE's F414 fighter engine. Testing of this engine will help evaluate many of the new HCF rules and tools utilized in its design.

The Pratt & Whitney XTE67/SE1 is an F119 based Structural Demonstrator Engine (SDE) that will be used to validate HCF design tools over the entire F-22 flight envelope.

LV100-5

The General Electric/ Honeywell LV100-5 turboshaft engine has been selected by the Army to power the General Dynamics M1 Abrams tank. IHPTET hot section technologies have contributed to the reduced weight, high reliability, and low operating costs of the engine.

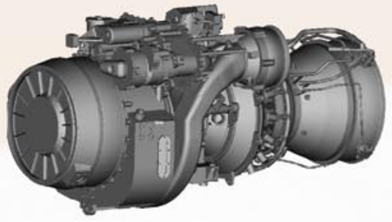


This Compressor Rotor Utilizing IHPTET Technologies has 40% fewer parts, half the stage count, and a 15 inch overall reduction in length, resulting in reduced weight and cost.

CEP

JTAGG technologies provide increased overall pressure ratio and combustor exit temperature capabilities for the Army's Common Engine Program (CEP). The CEP will replace the T700 and provide improved range and payload capability for the H-60 Blackhawk and AH-64 Apache helicopters.

JTAGG Developed Turbine Nozzles and Rotors offer high work designs with improved cooling, providing enhanced turbine durability.



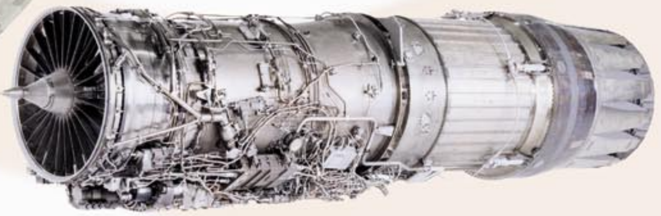
Axial-Centrifugal Compressor Technology, Demonstrated in a JTAGG I Core, will effectively reduce cost as well as provide high pressure ratio and higher temperature capability.

F100

Supercooled High Pressure Turbine Components are capable of providing a 3X increase in total accumulated cycle life at current F100-PW-229 thrust levels, or maintaining current turbine life at 20% increased thrust.

IHPTET continues to demonstrate advanced technologies, such as fan HCF characterization, damping, and CMC exhaust nozzle flaps. These technologies are available for transition to the F100 to increase thrust, reduce SFC, improve durability, and lower costs.

JP-8+100 Fuel, as Demonstrated on the F100 Engine, is transitioning to the F119, F135, and F136 engines to reduce coking, thereby increasing engine life and readiness while reducing operating and maintenance costs.

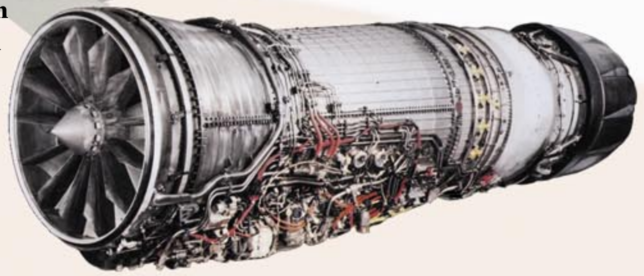


F110

Advanced Damperless Blisks deliver improved efficiency, pressure ratio, and flow rate with fewer parts.

This F110 Exhaust Nozzle Link is the first low risk production implementation of TMC materials, providing increased strength and reduced weight.

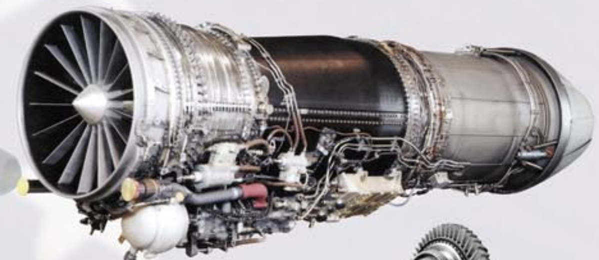
IHPTET technologies enabled a long chord blisk fan, composite fan duct, radial augmentor with 25% fewer parts, and hot section material and cooling improvements, providing over 10% thrust growth capability for the F110-GE-132 engine. Where additional thrust is not required beyond F110-GE-129 levels, these technologies can be exploited to provide up to a 50% increase in hot section life, with increased durability and reduced overall maintenance costs.



F414

Two Stage, Forward Swept Fan with Blisk Rotors (first stage shown) increases airflow and pressure ratio 10% over the current three stage version, and reduces parts count, weight, and manufacturing costs. Laser shock peening and translation friction welded blade repair reduces the effects of foreign object damage and lowers repair costs.

IHPTET technologies can reduce the F414 SFC by 4% and increase turbine life to 6,000 hours, providing a $2B savings in total ownership cost. These technologies could also be used to provide a 20% increase in thrust with a 2,000 hour turbine life. Improvements in component life and durability increase mean time between engine removals, leading to improved readiness and reduced maintenance cost.



This Six Stage Compressor uses the latest 3-D aero and clearance control features to increase efficiency by 3%. Also included are ruggedized leading edges, 3-D compound blisk hubs, non-uniform vane spacing, and probabilistic design assessment to significantly increase durability and reduce high cycle fatigue.

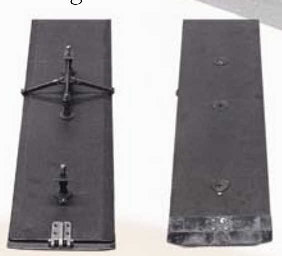
This Advanced High Pressure Turbine incorporates 3-D aero design, advanced cooling, and brush seals to increase efficiency by 2% and gas path temperature capability by 150°F with current blade materials.

F119

Advanced Materials provide an increase in temperature capability and creep resistance and enhance durability and system capability, while reducing maintenance cost.

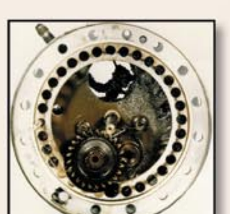
IHPTET continues to develop advanced technologies that are available for spiral transition into the F119 program. These provide the F119 with reduced SFC, up to a 10% increase in thrust, improved turbine durability, and reduced weight and life cycle cost.

Ceramic Matrix Composite Flaps and Seals will provide benefits in durability and wear while reducing weight and cost of the engine.



Advanced Damping Strategies Developed in the IHPTET HCF Program enhance durability and performance, resulting in reduced life cycle cost.

This Integrally Bladed Compressor Rotor is machined using advanced, low cost techniques. A variety of high performance machining concepts, including process modeling, advanced cutting tools, coolant application, and process control, are being used to lower fabrication costs and manufacturing cycle times.



MIL-L-7808J

MIL-PRF-7808L, GRADE 4

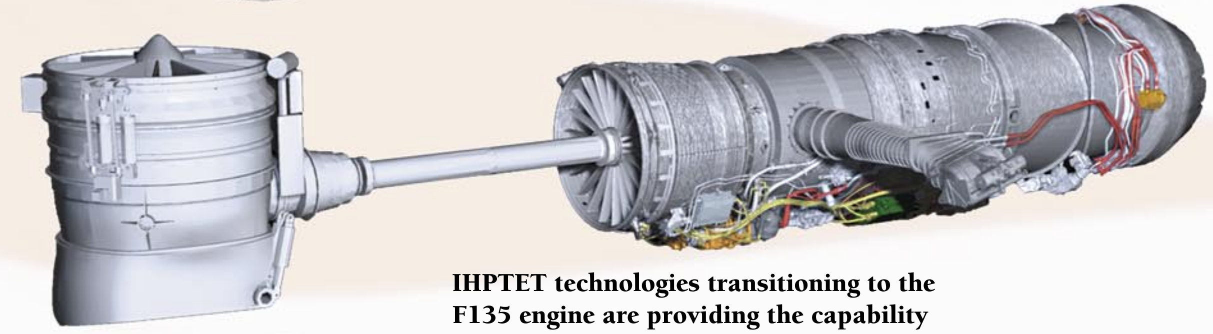
Rig Testing of MIL-PRF-7808L, Grade 4 Oil indicates it will provide a cleaner, higher temperature capability lubricant and is qualified for use in all military turbine engines.

...TECHNOLOGY IN TRANSITION

F135

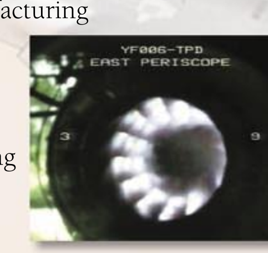
High Fuel-to-Air Ratio Combustor Technology is utilized to meet efficiency targets while providing decreased pattern factor and desired radial profiles.

The XTE67/1 "Super MAR" (Moderate Aspect Ratio) Fan Rotor was tested at the AFRL Compressor Research Facility. It incorporates forward sweep, linear friction welding, integrally bladed rotors, and mistuning technologies for reduced weight and cost.



IHPTET technologies transitioning to the F135 engine are providing the capability for improved durability, weight and cost reduction, high temperature operation, and enhanced performance.

Advanced Augmentor Concepts that Balance Thrust Performance and Low Observability are being developed using the latest modeling and manufacturing techniques. The advanced augmentor technology developed for the XTE67/1 JTDE has been transitioned into the F135 engine, providing state-of-the-art augmentor performance.

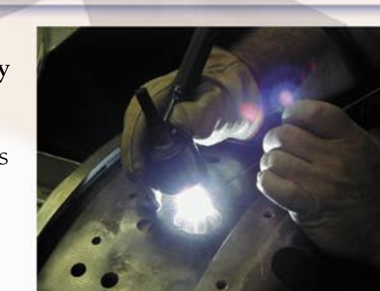


Supercooled Turbine Blades and Vanes, cast from higher temperature capable materials, allow increased operating temperatures with improved durability.

F136

The Cooling Effectiveness of this CASTBOND HPT Vane provides increased life at a reduced cooling flow level.

An Innovative Repair Procedure for a Lamilloy Combustor has been developed and adapted for depot repair and offers significant maintenance cost reduction.



This Hybrid Bearing with Ceramic Rolling Elements and Duplex Hardened Metallic Races provides 2.7 million DN capability and meets the 4,000 hour life requirement for the F136 engine number 3 bearing.

The F136 core test successfully demonstrated capabilities of the compressor, combustor, and turbine while proving many of the new technologies that are being incorporated into the engine.

An Organic Matrix Composite Duct, similar to this F110-GE-132 duct, will reduce engine weight by 20 pounds.

THE VERSATILE AFFORDABLE ADVANCED TURBINE ENGINES PROGRAM IS FOCUSED ON ACHIEVING A 10X IMPROVEMENT IN TURBINE ENGINE AFFORDABILITY...

VAATE MISSION

To develop, demonstrate, and transition

ADVANCED

multi-use, Turbine Engine technologies that provide a revolutionary improvement in

AFFORDABILITY

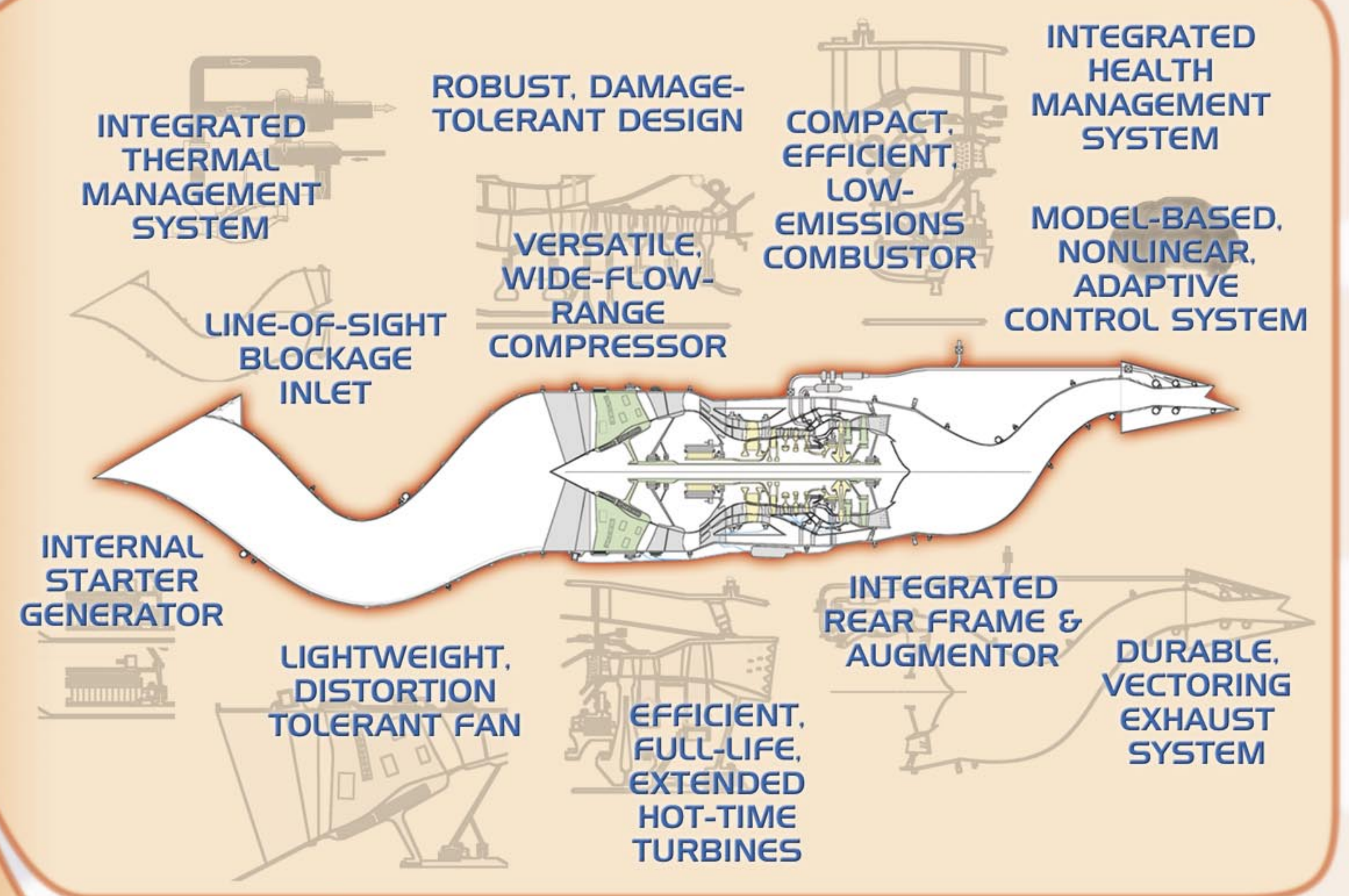
to a broad range of legacy, pipeline, and future military propulsion and power needs, with explicit

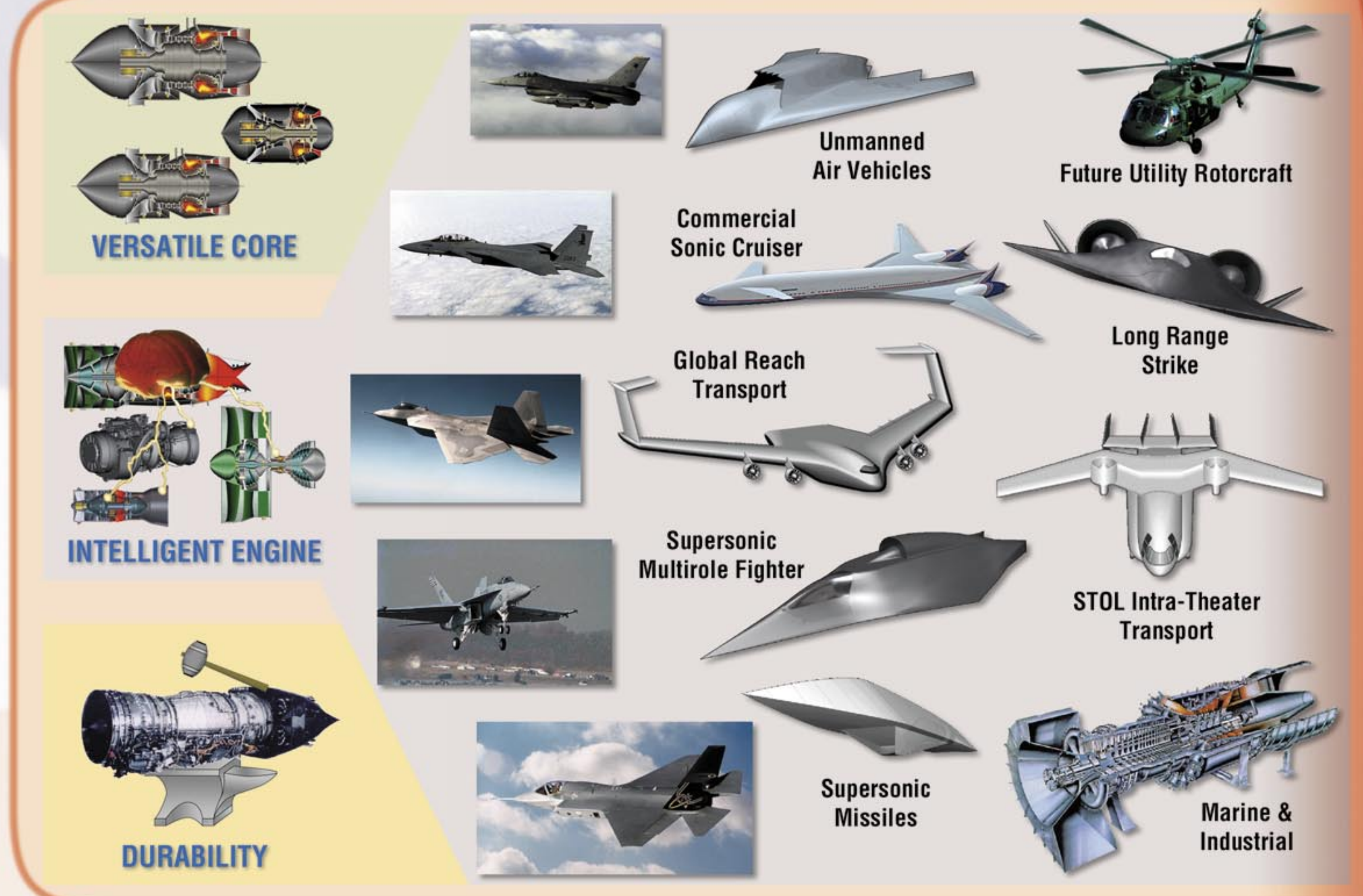
VERSATILITY

for dual-use application.

VAATE Versatile Affordable Advanced Turbine Engines 10X — Versatile Core • Durability • Intelligent Engine

Honeywell · NASA · AADC · Williams International · CONTINENTAL MOTORS · BOEING · DARPA · NORTHROP GRUMMAN · LOCKHEED MARTIN





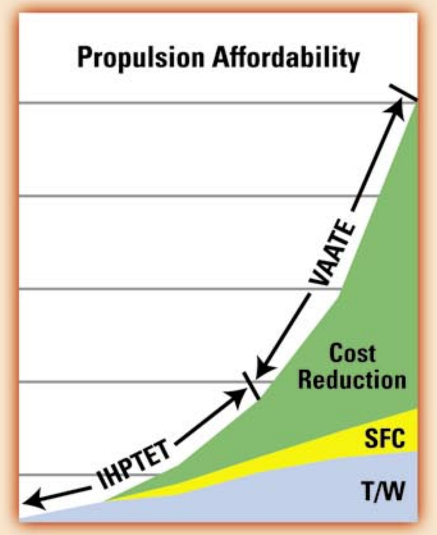
AFFORDABILITY METRIC ESTABLISHED FOR VAATE

$$\text{CCI} = \text{Propulsion Capability/Cost Index} = \frac{\Delta\text{Capability}}{\Delta\text{Cost}}$$

Where: Cost is a Function of Development, Production and Maintenance Costs.

Lower Development Cost
- Applied Virtual Design/Testing
- Rapid Technology Maturation
- Early Engine/Airframe Integration
- Shared System Development

Lower Production Cost
- Multisystem Hardware
- Advanced Manufacturing
- Lower Parts Cost
- Innovative Assembly
- Reduced Parts Count



Lower Maintenance Cost
- Maintenance Free Focus
- Damage-Tolerant Design
- Reduced Unscheduled Removal Rate
- Health Management
- Increased Hot-Time Capability
- Enhanced Life
- Repairable Components
- Improved Inspection Methods

VAATE STEERING COMMITTEE

OSD • Air Force • Navy • Army • DARPA • NASA • DOE

Industry Panel

AADC · General Electric · Pratt & Whitney · Williams International · Honeywell · Teledyne · Boeing · Northrop-Grumman · Lockheed-Martin

Focus Areas

Versatile Core · Intelligent Engine · Durability

Pervasive Panels

Modeling & Simulation · Materials · Emissions & Noise · ManTech · High Impact Technologies

Technology Applications Panels

UAV-Unique Applications · Emerging Aerospace Applications · Non-Aerospace Applications · Legacy Applications

VAATE AFFORDABILITY METRIC GOALS

CAPABILITY/COST INDEX*

	VAATE I 2010	VAATE II 2017	PHYSICS-BASED GOAL FACTORS
Large Turbofan/Jet	6X	10X	Δ(Thrust/Weight) / ΔSpecific Fuel Consumption / ΔCost (Development + Production + Maintenance)
Small Turbofan/Jet**	5X	8X	
Turboshaft/Prop	3X	5X	Δ(Horsepower/Weight) / ΔSpecific Fuel Consumption / ΔCost (Development + Production + Maintenance)
Expendable	6X	10X	Δ(Thrust/Weight) / ΔSpecific Fuel Consumption / ΔCost (Development + Production)

VAATE GOAL FACTORS

Large Turbofan/Jet – (Government Example)

Capability	Baseline*	IHPTET	VAATE I	VAATE II
T/W (@ Max Power)	6.4	12 (1.9X)	16 (2.5X)	20 (3X)
SFC (SLS, Mil Power)	0.860	0.740 (-14%)	0.688 (-20%)	0.645 (-25%)
Cost (FY00 $'s)***	Base	-30%	-50%	-60%
Development	$1.85B	–	$0.92B	$0.63B
Production	$230/lb Fn	$152/lb Fn	$115/lb Fn	$92/lb Fn
Maintenance****	$1,300/EFH	$845/EFH	$650/EFH	$520/EFH
Capability/Cost Index (CCI)	**Base**	**3.1X**	**6X**	**10X**

* Baseline 2000 State-of-the-Art ** <20,000 lbs Thrust

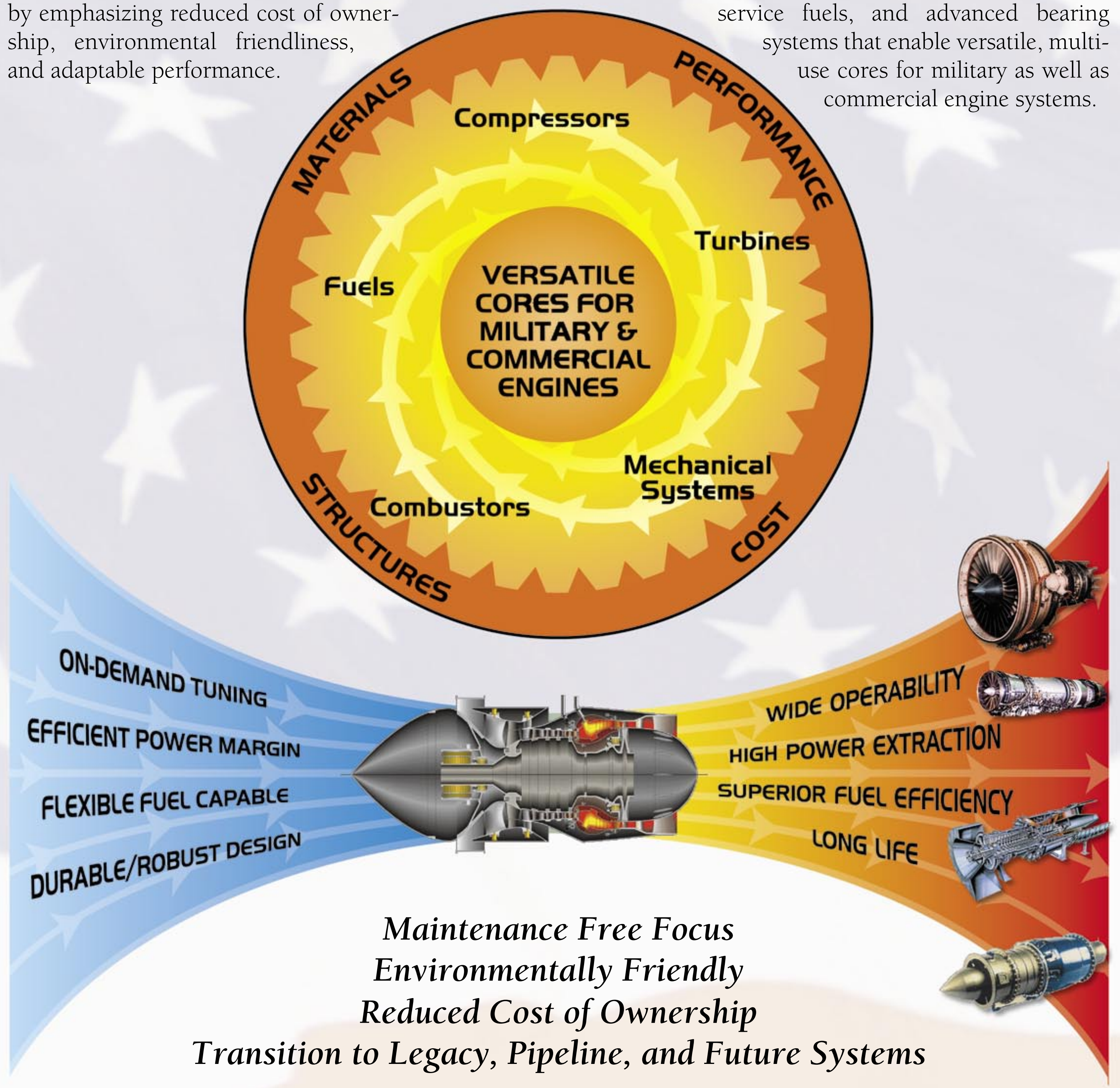
*** Total Cost Based on Weighting Factors as a Function of Total Life Cycle Cost and Yearly Expenditures ΔCost = 0.1(ΔDevelopment $) + 0.5(ΔProduction $) + 0.4(ΔMaintenance $)

**** Includes Depot Costs but not Fuel Costs

VERSATILE CORE FOCUS AREA...

Mission
Develop and demonstrate affordable, multi-use core technologies for transition to a broad range of legacy, pipeline, and future military propulsion and power systems, with explicit dual-use capability by emphasizing reduced cost of ownership, environmental friendliness, and adaptable performance.

Action Teams
The Versatile Core Action Teams will develop technologies such as high pressure ratio compressors, homogeneous mixing and combustion, highly efficient turbines, innovative structural concepts, multi-service fuels, and advanced bearing systems that enable versatile, multi-use cores for military as well as commercial engine systems.



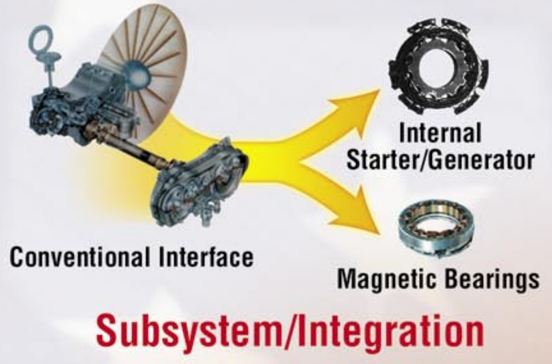
Maintenance Free Focus
Environmentally Friendly
Reduced Cost of Ownership
Transition to Legacy, Pipeline, and Future Systems

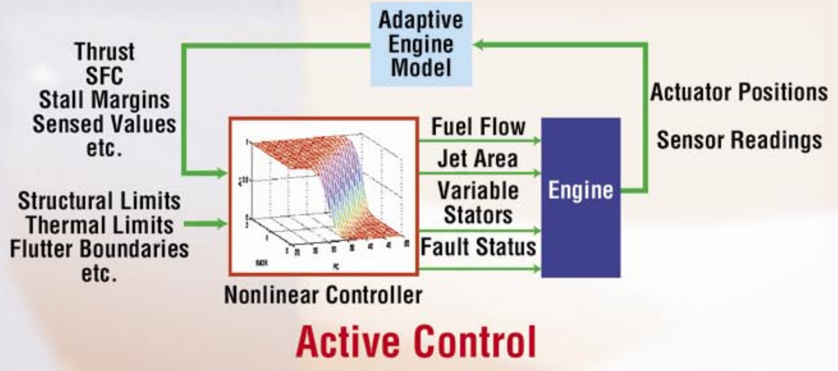
Adaptable to Changing System Requirements (Multi/Dual-Use)

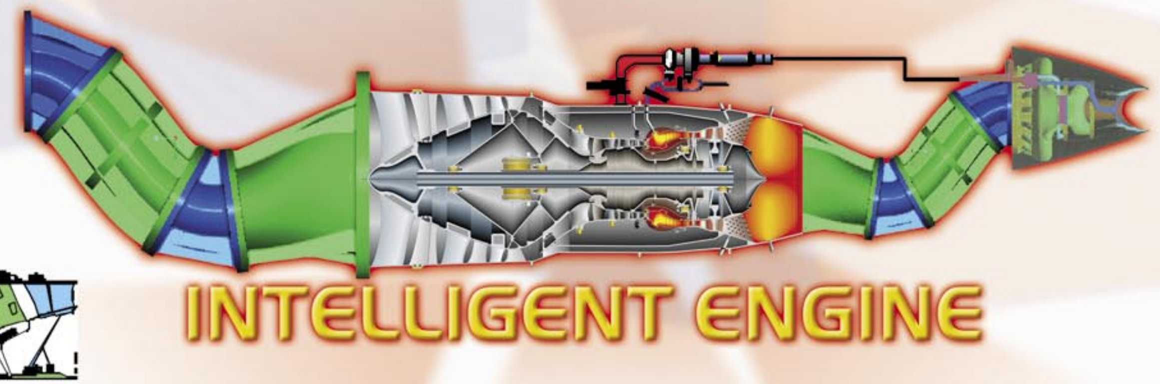
INTELLIGENT ENGINE FOCUS AREA...

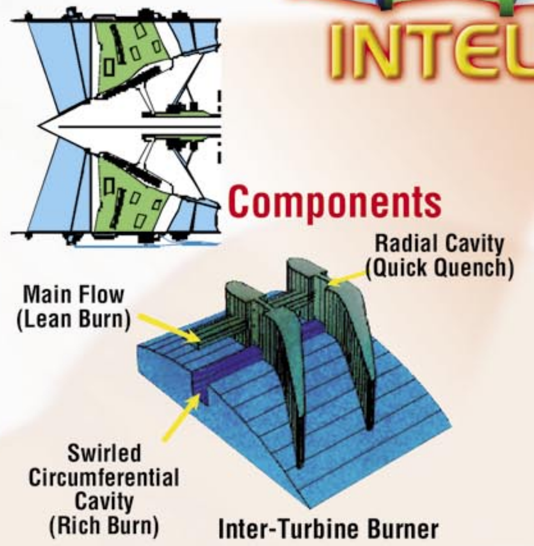
Mission
Develop, demonstrate, and transition advanced aerodynamics, materials, and structural concepts in combination with emerging active control, health management, aircraft subsystem integration, and information technologies to bring new levels of capability, survivability, and affordability to legacy, pipeline, and future engines for expendable, unmanned, and manned weapon systems.

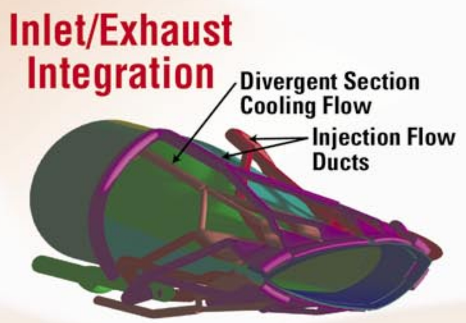
Action Teams
The Intelligent Engine Action Teams have been formed to facilitate program planning and execution in the many diverse Intelligent Engine research areas. A Components Action Team serves as the linchpin for teams specializing in active control, engine health management, inlet and exhaust system integration, and subsystem (power and thermal management) integration by providing system requirements and coordinating the needs of the other teams.









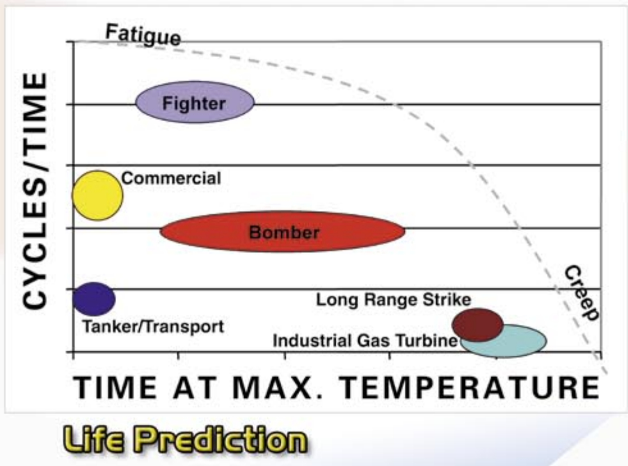


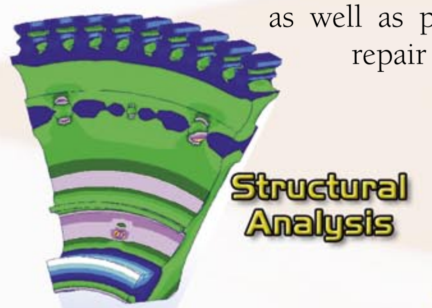
Self-Optimizing, Self-Diagnosing, Mission-Adaptable

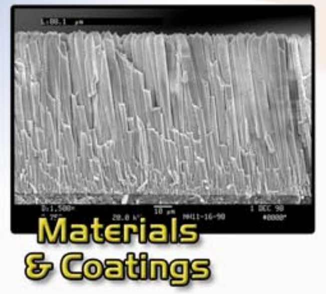
DURABILITY FOCUS AREA...

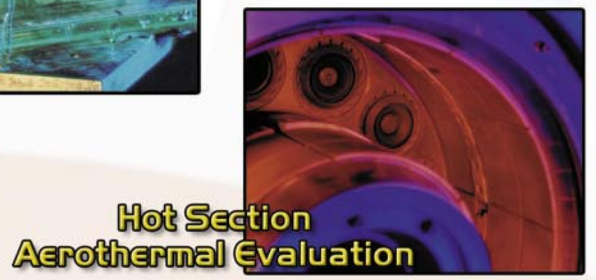
Mission
Work directly with the field to make high performance turbine engine technology affordable to the user through proactive development of advanced technologies to prevent component failure, increase engine life and reliability, enhance repairability, and reduce costs for improved warfighter readiness.

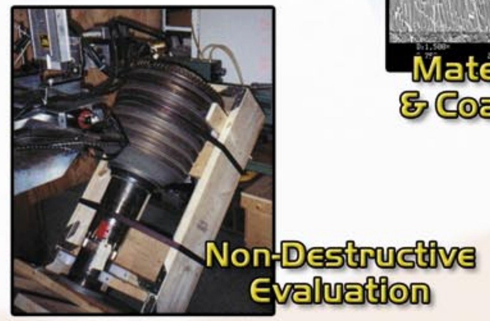
Action Teams
The Durability Action Teams are working to significantly extend component life and to reduce the maintenance costs of future engines, while emphasizing those technologies which can be retrofitted to legacy engines to provide additional component life and maintenance cost reductions. This split focus of addressing both existing and future engine maintenance costs is reflected in the Durability mission statement. The Durability Focus Area will double component life while providing a significant increase in hot-time capability, as well as providing reductions in repair and development costs.











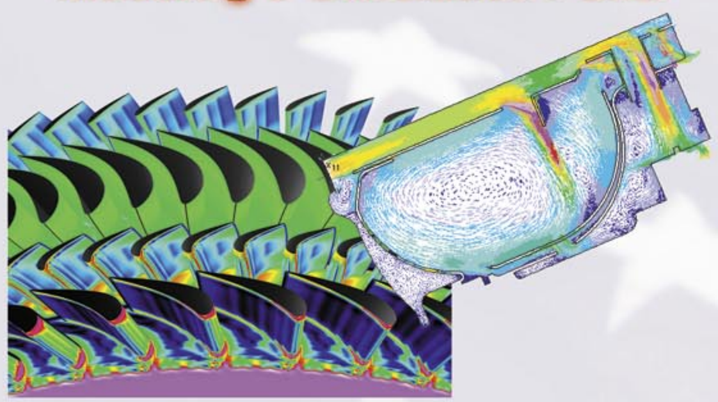
Improving Readiness, Reducing Costs

PERVASIVE PANELS...

Mission

Pervasive Panels provide technology support to the three Focus Areas. These Panels include Materials, Manufacturing Technologies, Emissions & Noise, and Modeling & Simulation. The fifth Panel, High Impact Technologies, is incubating the revolutionary high risk/payoff concepts required to meet the ultimate goals of VAATE II.

Modeling & Simulation Panel

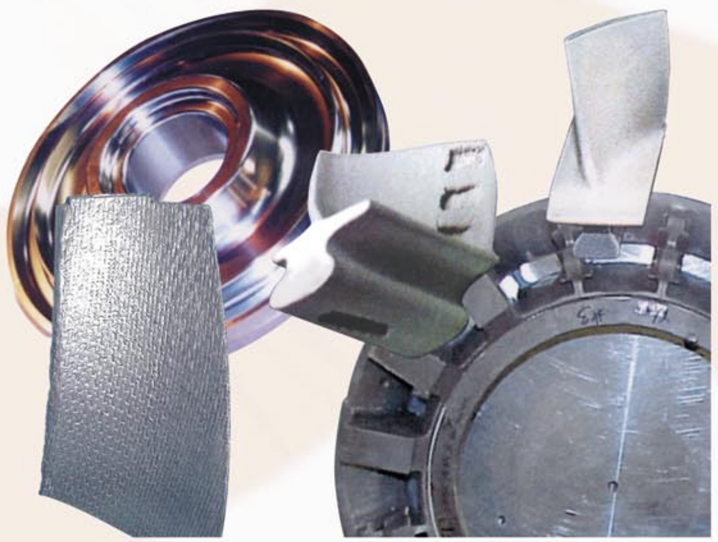


Emissions & Noise Panel

High Impact Technologies Panel

ManTech Panel

Materials Panel

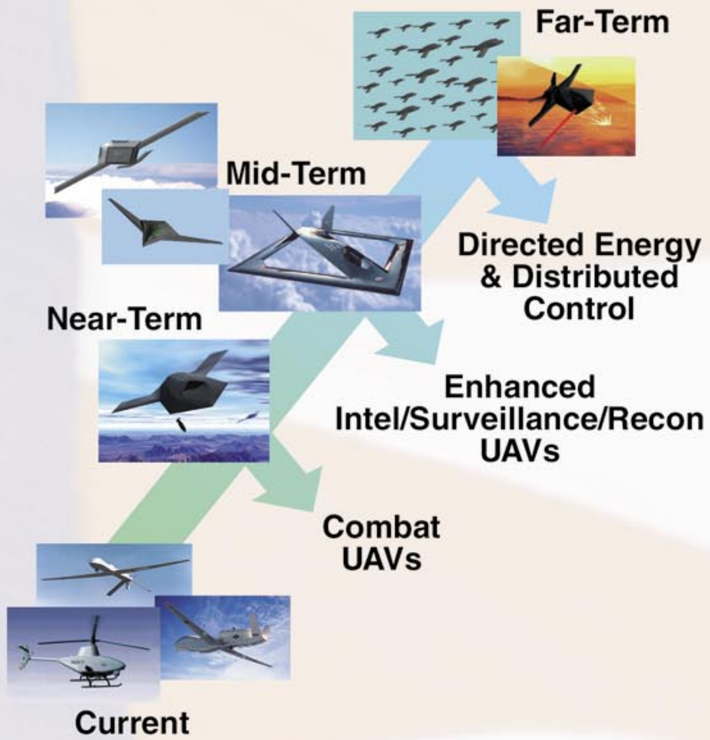


TECHNOLOGY APPLICATIONS PANELS...

Mission

Technology Applications Panels streamline the flow of VAATE technologies to our customers. These panels include Unmanned Air Vehicle (UAV) Unique Applications, Emerging Aerospace Applications, Non-Aerospace Applications, and Legacy Applications. These Technology Applications Panels establish direct ties to the customer which ensures rapid transition into current and future systems, integrating VAATE program results with desired capabilities.

UAV - Unique Applications Panel



Emerging Aerospace Applications Panel

Non-Aerospace Applications Panel

Legacy Applications Panel

THE TURBINE ENGINE TECHNOLOGY BUSINESS PLAN ENSURES A SPIRAL-BASED, RAPID TRANSITION INTO LEGACY, PIPELINE, AND FUTURE WEAPON SYSTEMS

IHPTET PHASE II & III — 2X CAPABILITY BY 2005

VAATE I — 6X AFFORDABILITY BY 2010

HIGH IMPACT TECHNOLOGIES

VAATE II — 10X AFFORDABILITY BY 2017

F-15

F-16

F100/F110 ENGINES

- Up to 50% Life Increase
- Up to 25% Thrust Increase
- Up to 7% Range Increase
- Up to $1.3B Disk Replacement Cost Avoidance
- Potential $2.5B Life Cycle Cost Savings with Technology Insertion

F-22

F119 ENGINE

- 10% Thrust Increase
- 5% Range Increase
- Potential $1.25B Life Cycle Cost Savings with Technology Insertion

F/A-18E/F

F414 ENGINE

- 5% Longer Range
- 20% Increased Thrust or $1B-$2B Total Ownership Cost Savings
- Increased Time on Wing
- Improved Readiness

F-35 JSF

F135/F136 ENGINES

- Greater Than 244 Pounds Weight Avoidance
- Greater Than 10% Thrust Growth
- Greater Than $315K Production Cost Avoidance Per Engine
- Greater Than $6B Life Cycle Cost Avoidance

Global Hawk

AE3007 ENGINE

- 50% Increased Payload or 65% Increased Time on Station
- Greater Than 2X Increase in Aircraft Available Power

H-60/AH-64

COMMON ENGINE PROGRAM

- 20% Reduction in Acquisition, Operation, and Support Costs
- 20% Life Increase
- 80% Increase in Payload at Equivalent Radius
- Double Mission Radius with Equivalent Payload

Long Range Strike

ADVANCED SUPERSONIC CRUISE ENGINE

- Mach 2-4 Cruise Capability
- 30% Increased Mission Radius
- Potential $9.0B Life Cycle Cost Savings with Technology Insertion
- 3X Increased Sortie Generation Rate
- Fast Response to Time Critical Targets

USAF UCAV

Navy UCAV

Supersonic UCAV

ADVANCED UCAV ENGINE

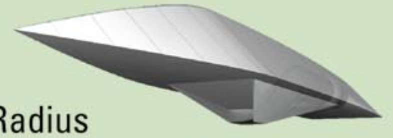
Subsonic Vehicle:

- 150% Radius Increase or 3X Loiter Time
- Potential $1.3B Life Cycle Cost Savings with Technology Insertion

Supersonic Vehicle:

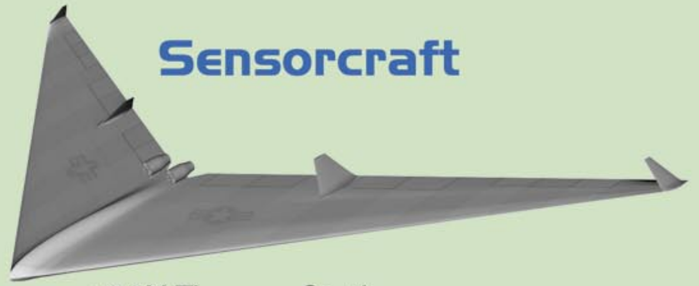
- Enables Supersonic Cruise Capability
- 2-3X Sortie Generation Rate Potential
- Fast Response to Time Critical Targets

Supersonic Missile



- 2X Radius
- Mach 3.5 Cruise Capability
- Fast Response to Time Critical Targets

Sensorcraft

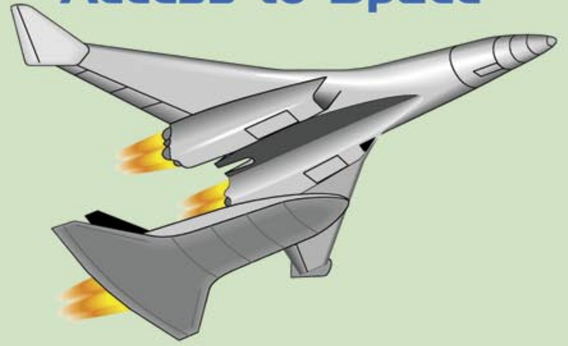


- 2.1X Time on Station
- 24/7 Coverage with 2 Aircraft

Future Cargo Helicopter

- Future Combat System Transport Capability
- 4X Range or 2X Payload
- Global Self-Deployment

Access to Space



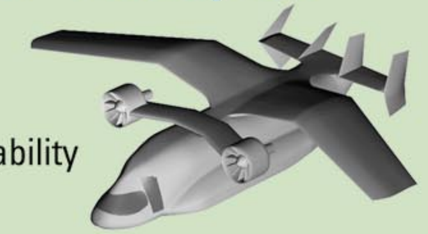
- Mach 4+ Capable Accelerator
- Affordable Access to Space

Large Commercial Passenger

- 33% Range Increase
- 17% Reduction in Cost/Seat-nm

Ultra-Short Takeoff & Landing Intra-Theater Transport

- 1.3X C-130 Cruise Speed
- 30% Increase in Radius
- Short Takeoff/Landing Capability



LEGACY | PIPELINE | FUTURE

CAPABILITY-BASED TECHNOLOGY INSERTION IS THE CORNERSTONE OF OUR EFFORTS TO RAPIDLY MEET THE WARFIGHTER'S NEEDS